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THE CONTROL ANTICIPATION PARAMETER FOR AUGMENTED AIRCRAFT.(U)
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THE CONTROL ANTICIPATION PARAMETER FOR AUGMENTED AIRCRAFT

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A longitudinal control anticipation parameter is developed which correlates high order augmented aircraft dynamics with both lower order equivalent system descriptions and pilot opinion ratings. Three extensive in-flight research programs are analyzed via the developed parameter in an effort to define regions of pilot acceptability. Additional effort is recommended to verify the minimum level 1 boundaries and to determine the relationship between the control anticipation parameter and alternate proposed criteria.

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LIST OF SYMBOLS

CAP	- Control Anticipation Parameter - rad/sec^2/g
CAP'	- Attenuated Control Anticipation Parameter - rad/sec^2/g
F	- Pilot force input - lb
K_θ	- Gain of pitch rate to control input transfer function
$L\alpha$	- Inverse numerator time constant, Dimensional lift curve slope
n/α	- Acceleration sensitivity parameter - g/rad
n_z	- Normal acceleration - g's
$M_{\delta e}, M_w, M_q$	- Pitching moment stability derivative due to control input, vertical velocity and pitch rate, respectively
s	- Laplace frequency domain variable
td	- Equivalent system time delay - sec
$T_{\theta 2}$	- Pitch rate numerator time constant - sec^{-1}
V	- Freestream velocity - ft/sec
$Z_{\delta e}, Z_w$	- Normal force stability derivative due to control input and vertical velocity, respectively
α	- Angle of attack - rad
δc	- Pilot control input - rad
δe	- Elevator (stabilizer) position - rad
θ	- Pitch angle - rad
$\dot{\theta}, q$	- Pitch rate - rad/sec
$\ddot{\theta}$	- Pitch acceleration - rad/sec^2
ω_n	- Undamped natural frequency - rad/sec
ζ	- Damping ratio

Subscripts

e	- Equivalent system
FS	- Feel system
sp	- Short period
ss	- Steady state
nd	- Nondimensional

THE CONTROL ANTICIPATION PARAMETER FOR AUGMENTED AIRCRAFT

INTRODUCTION

The military flying qualities specification, MIL-F-8785B (reference (a)) specifies airplane short period frequency (ω_{nsp}) requirements as a function of acceleration sensitivity (n/α) as shown in Figure 1. The boundaries for minimum and maximum frequency requirements have been established from piloted flight tests as lines of constant $\omega_{nsp}^2/n/\alpha$. Using the assumption that the responses of interest to a pilot during a pullup are the initial pitch acceleration and steady state normal acceleration, Bihrle (reference (b)) defined a control anticipation parameter (CAP) as the ratio of these two parameters. He further showed that in the short period approximation, CAP is equal to $\omega_{nsp}^2/n/\alpha$.

Both the 8785B requirements and Bihrle's analysis were developed using unaugmented aircraft for which the control system's dynamic effects were assumed to be negligible. If higher order dynamics are included in the system description, this simple relationship may no longer hold. For example, the implementation of a washed out pitch rate feedback does not alter either the initial pitch acceleration or the study state normal acceleration, thereby not affecting CAP. However, the short period frequency may be significantly changed causing $\omega_{nsp}^2/n/\alpha$ to differ from CAP. If feel system or actuator dynamics are included in the system model, the initial pitch acceleration is identically zero, building to a maximum some time after the input is applied. Difranco studied this problem and defined on attenuated CAP, CAP', which took into account the effects of the feel system's dynamics, reference (c).

The latest revision to the military flying qualities specification, MIL-F-8785C (reference (d)) imposes the short period requirements of -8785B on aircraft possessing higher order control system dynamics by allowing the determination of equivalent lower order system characteristics which approximate the higher order system. While it may be argued that it is possible to determine equivalent lower order systems having similar time responses to those of the actual higher order systems, correlation of the resulting parameters with MIL-SPEC requirements has produced some perplexing results. For example, aircraft possessing complex control systems, whose dominant roots appear to lie in the acceptable regions of Figure 1, yield equivalent systems whose ω_n versus n/α relationship crosses the minimum frequency boundaries into unacceptable regions (Figure 2). However, the time histories for such responses show little difference from those of the higher order systems from which they were developed. Further, analysis of the control anticipation parameter (by measuring the maximum slope of pitch rate and steady state n_z) for each of these responses, does not correlate either. Therefore, it is difficult to interpret what a pilot's opinion of such responses would be from analysis of these model parameters.

The purpose of this memorandum is to provide a definition of the control anticipation parameter for higher order systems which will (1) correlate with the frequency/acceleration sensitivity relationship of the higher order system and (2) be consistent with the modal parameters obtained from the lower order equivalent. This will be accomplished by briefly reviewing Bihrle's and DiFranco's developments and then extending them to general higher order cases. Examples from current Navy fleet aircraft and contractor flight research programs will be utilized to illustrate the analysis.

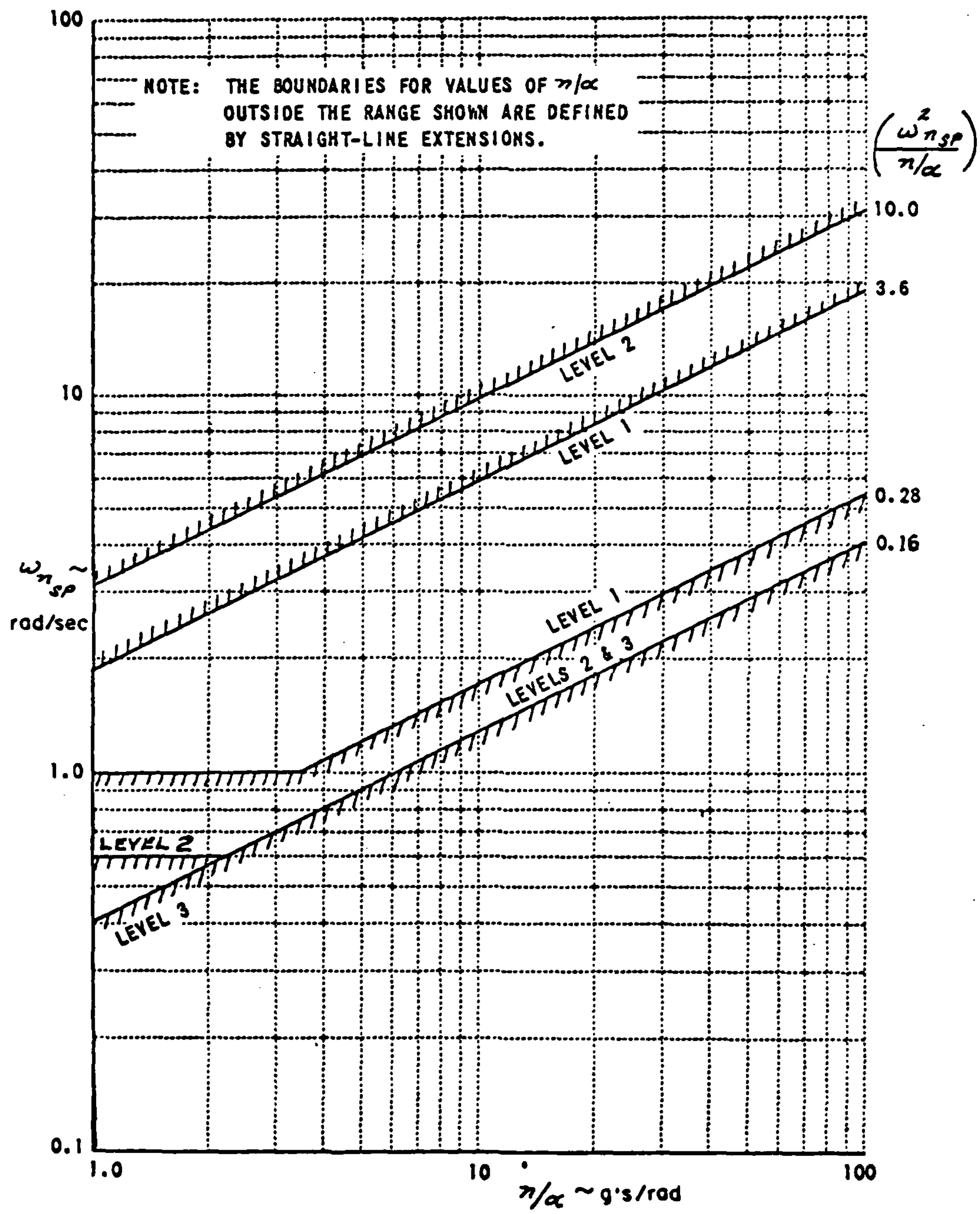


FIGURE 1. MIL-F-8785B Short Period Frequency Requirements

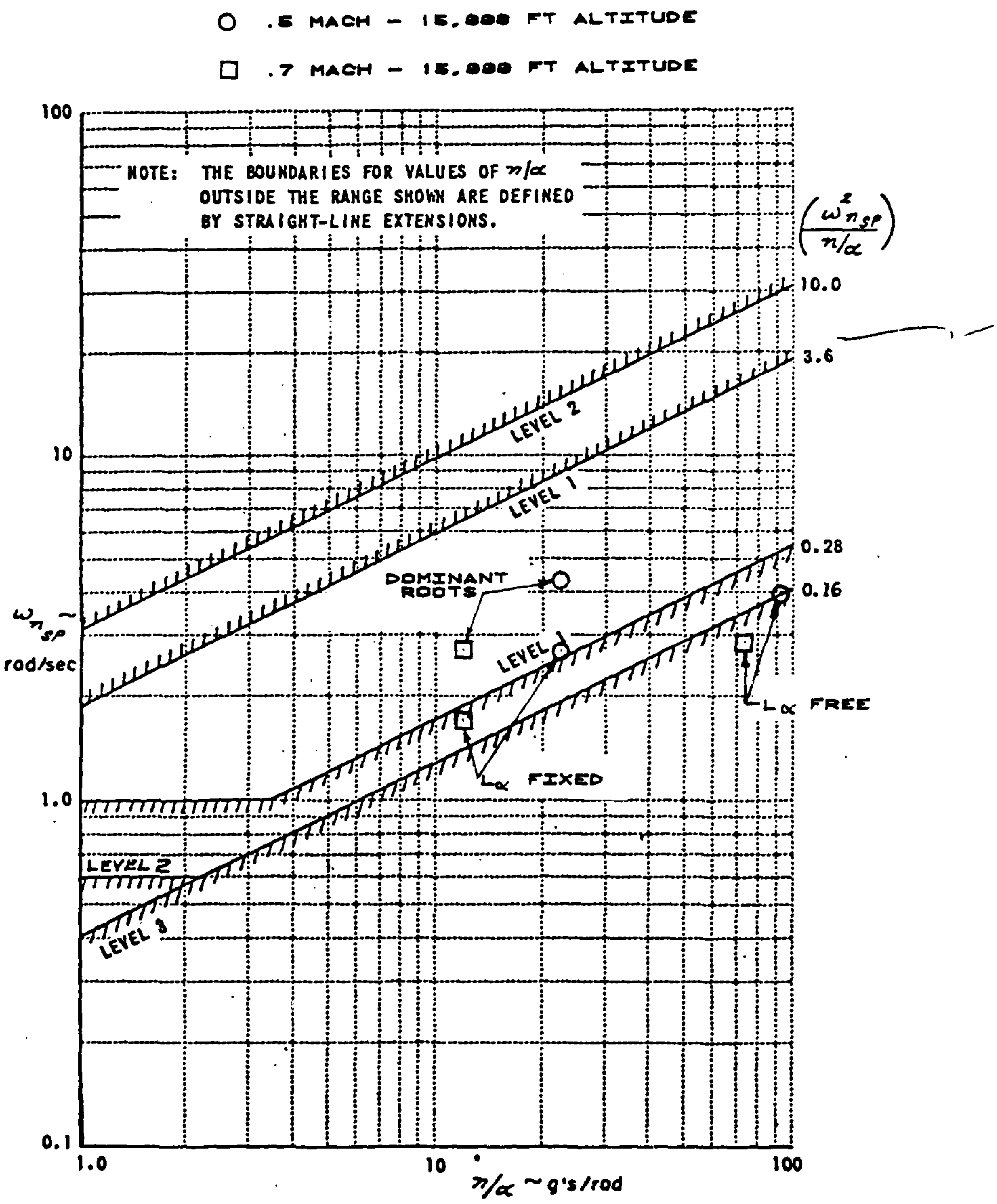


FIGURE 2. F-14 Equivalent Short Period Frequency Parameters

CONTROL ANTICIPATION PARAMETER DEVELOPMENT

Under the assumption of constant speed equations of motion, the approximate transfer functions relating the short period pitch response of an aircraft to an elevator input can be expressed as -

$$\frac{\theta(s)}{\delta e(s)} = \frac{K_\theta (s + 1/T_{\theta_2})}{s(s^2 + 2\zeta_{sp}\omega_{n_{sp}} s + \omega_{n_{sp}}^2)} \qquad (1)$$

$$\frac{\dot{\theta}(s)}{\delta e(s)} = \frac{s\,\theta(s)}{\delta e(s)} \qquad \frac{\ddot{\theta}(s)}{\delta e(s)} = \frac{s^2\,\theta(s)}{\delta e(s)}$$

The initial pitch acceleration response to a unit step elevator input is obtained from

$$\ddot{\theta}(0) = s\,\ddot{\theta}(s)\Big|_{s\to\infty} = \frac{s\ddot{\theta}(s)}{\delta e(s)} \cdot \frac{1}{s}\Big|_{s\to\infty}$$

$$= \frac{s^2 K_\theta (s + 1/T_{\theta_2})}{s^2 + 2\zeta_{sp}\omega_{n_{sp}} s + \omega_{n_{sp}}^2}\,\frac{1}{s}\Big|_{s\to\infty}$$

$$\therefore\ \ddot{\theta}(0) = K_\theta \qquad (2)$$

The steady state normal acceleration may be determined from the relationship

$$n_{z_{ss}} = \frac{V}{g}\, q_{ss}$$

where

$$q_{ss} = \frac{s\,\theta(s)}{\delta e(s)}\,\frac{1}{s}\Big|_{s\to\infty}$$

$$= \frac{K_\theta (1/T_{\theta_2}}{\omega_{n_{sp}}^2}$$

$$\therefore\ n_{z_{ss}} = \frac{V}{g}\,\frac{K_\theta (1/T_{\theta_2})}{\omega_{n_{sp}}^2} \qquad (3)$$

Bihrle's control anticipation parameter, defined as the ratio of initial pitch acceleration to steady state normal acceleration, may be expressed as:

$$CAP = \frac{\ddot{\theta}(o)}{n_{z_{ss}}} = \frac{K_\theta}{\frac{V}{g}\frac{K_\theta}{\omega_{n_{sp}}^2}\left(\frac{1}{T_{\theta_2}}\right)} = \frac{\omega_{n_{sp}}^2}{\frac{V}{g}\left(\frac{1}{T_{\theta_2}}\right)} \quad (4)$$

It can also be shown from the equations relating n_z and α to elevator inputs that:

$$\frac{n}{\alpha} = \frac{\Delta n}{\Delta \alpha} = \frac{V}{g}\left(\frac{Z_{\delta e} M_w - M_{\delta e} Z_w}{M_{\delta e} - \frac{Z_{\delta e} M_q}{V}}\right) \quad (5)$$

which for

$$|M_{\delta e}| >> (Z_{\delta e} M_q / V)$$

reduces to

$$\frac{n}{\alpha} = \frac{V}{g}\left(\frac{Z_{\delta e} M_w - M_{\delta e} Z_w}{M_{\delta e}}\right) \approx \frac{V}{g}\left(\frac{1}{T_{\theta_2}}\right) \quad (6)$$

Therefore:

$$CAP = \frac{\ddot{\theta}(o)}{n_{z_{ss}}} = \frac{\omega_{n_{sp}}^2}{n/\alpha} \quad (7)$$

DiFranco expanded this analysis to include feel system dynamics. In this case, the pitch response to pilot force inputs is defined by:

$$\frac{\dot{\theta}(s)}{F(s)} = \frac{K_\theta(s + 1/T_{\theta_2})}{(s^2 + 2\zeta_{sp}\omega_{n_{sp}} s + \omega_{n_{sp}}^2)} \cdot \frac{\omega_{FS}^2}{(s^2 + 2\zeta_{FS}\omega_{FS} s + \omega_{FS}^2)} \quad (8)$$

The initial pitch acceleration response to a unit step force input is now found to be zero:

$$\ddot{\theta}(0) = s\,\ddot{\theta}(s)\Big|_{s\to\infty} = \frac{s\,\ddot{\theta}(s)}{F(s)}\,\frac{1}{s}\Big|_{s\to\infty}$$

$$= \frac{s\,s^2\,\theta(s)}{F(s)}\Big|_{s\to\infty}$$

$$= 0$$

The maximum pitch acceleration occurs at some time (greater than $t = 0^+$) after the input is applied and is attenuated from that obtained without feel system dynamics (Figure 3). An attenuation factor, $\ddot{\theta}_{nd}$, relating the maximum pitch acceleration, including feel system dynamics, to the initial pitch acceleration, excluding feel system dynamics, in response to a step stick force input, can be expressed as:

$$\ddot{\theta}_{nd} = \frac{\ddot{\theta}_{max\ FS}}{\ddot{\theta}(0)_{w/o\ FS}}$$

$$= \frac{\omega_{FS}^2\,(s + 1/T_{\theta_2})}{(s^2 + 2\zeta_{sp}\omega_{n_{sp}}s + \omega_{n_{sp}}^2)(s^2 + 2\zeta_{FS}\,\omega_{FS}\,s + \omega_{FS}^2)} \qquad (9)$$

where $\ddot{\theta}_{nd}$ is now a nondimensional pitch acceleration. The value of $\ddot{\theta}_{nd}$ can be determined by converting equation (9) to a time function and finding its maximum value. For any particular aircraft flight condition, as ω_{sp} is increased, the value of $\ddot{\theta}_{nd}$ will be reduced, i.e., the attenuation will become greater (Figure 4).

⊙·······⊙ BARE AIRFRAME $\frac{\dot{\theta}(s)}{\delta(s)} = \frac{(1.78)}{[.7,4]}$

——— BARE AIRFRAME PLUS FEEL SYSTEM $\frac{\dot{\theta}(s)}{\delta(s)} = \frac{529(1.78)}{[.66,23][.7,4]}$

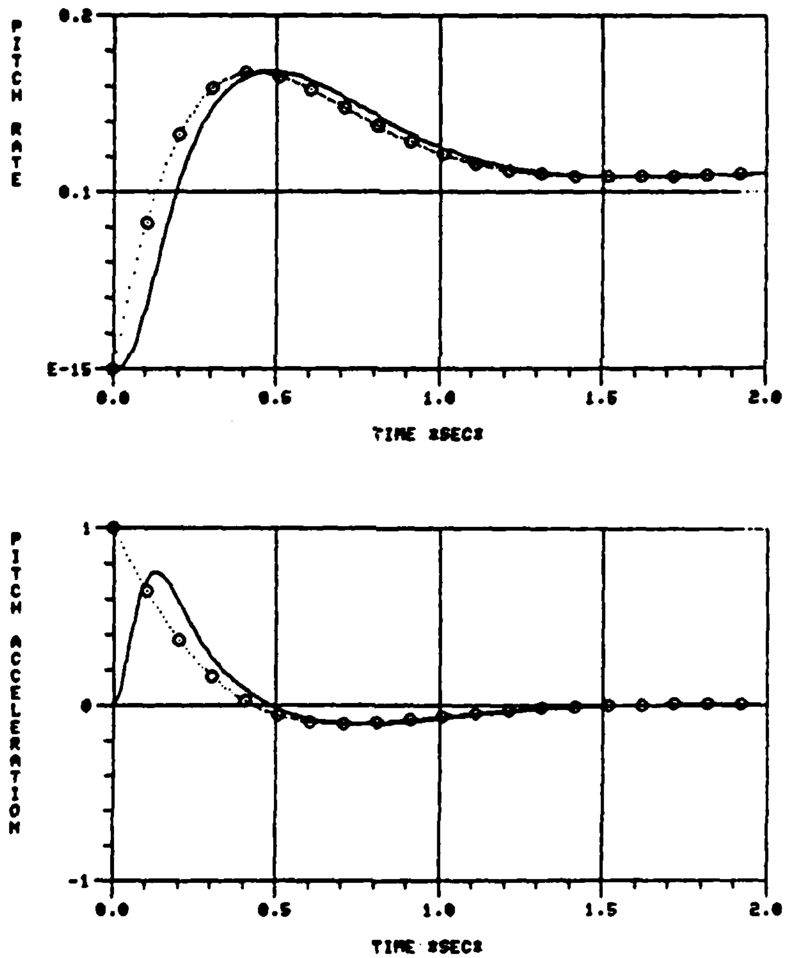


FIGURE 3. Attenuation Effect of Feel System Dynamics on Pitch Response

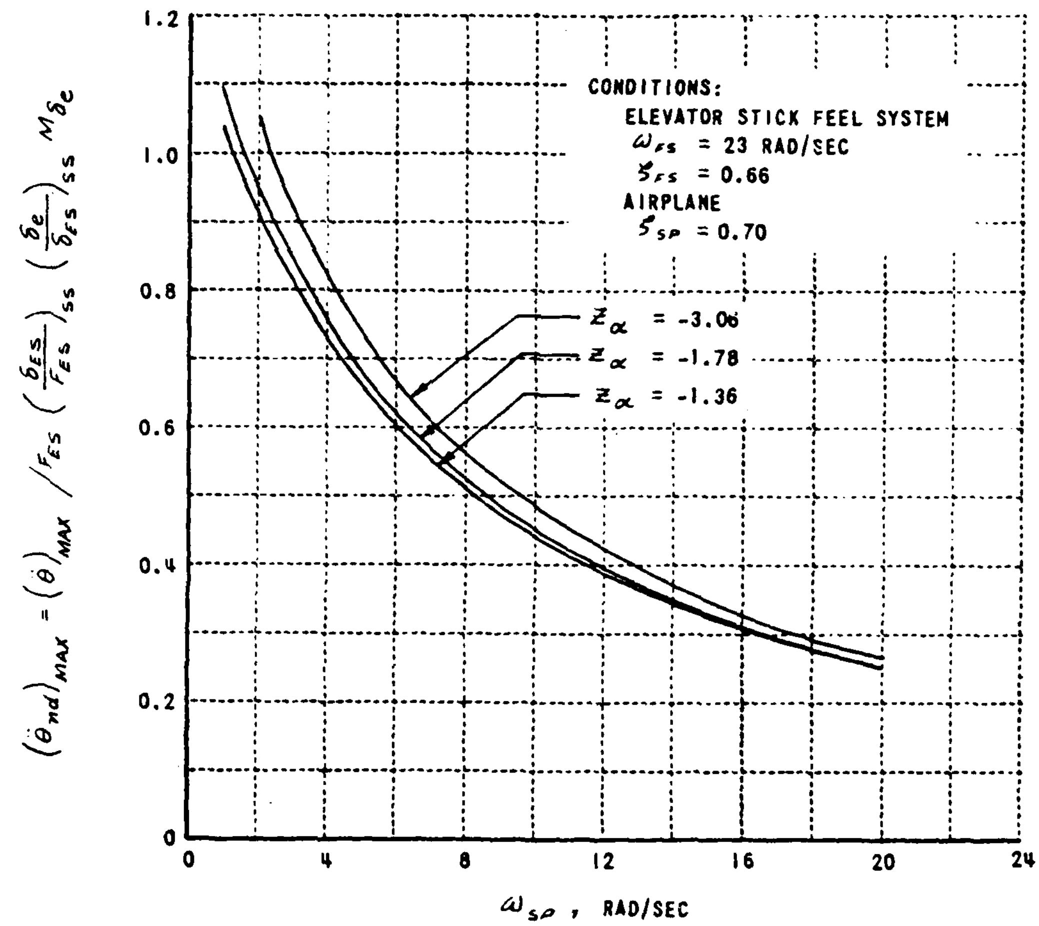


FIGURE 4. Attenuation Effects of Aircraft Dynamics on Maximum Pitch Acceleration (Reference (c) figure)

The steady state normal acceleration, following a step stick force input, is now determined as:

$$n_{z_{ss}} = \frac{V}{g} q_{ss} = \frac{V}{g} \frac{s\Theta(s)}{F(s)} \frac{1}{s} \Big|_{s \to 0}$$

$$= \frac{V}{g} \frac{\omega_{FS}^2 K_\theta (1/T_{\theta_2})}{\omega_{FS}^2 \omega_{n_{sp}}^2} \qquad (10)$$

which is unchanged from the case in which feel system dynamics were excluded. Substituting equations (9) and (10) into the expression for CAP yields

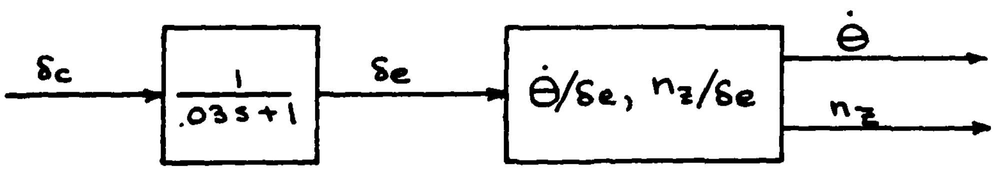
$$CAP = \frac{\ddot{\theta}_{max\ FS}}{\ddot{\theta}_{nd}\ n_{z_{ss}}} = \frac{\omega_{n_{sp}}^2}{n/\alpha} \qquad (11)$$

DiFranco further defined CAP' to include the attenuating effects of feel system dynamics as

$$CAP' = \frac{\ddot{\theta}_{max\ FS}}{n_{z_{ss}}} = \frac{\omega_{n_{sp}}^2}{n/\alpha} \ddot{\theta}_{nd} \qquad (12)$$

Examination of this last equation provides insight into the problems of mapping higher order system short period characteristics onto specification requirements and attempting to correlate them with the pitch and normal acceleration responses experienced by the pilot. The frequency and acceleration sensitivity point plotted on the MIL-SPEC requirements should not be compared with lines of constant CAP, but with lines of constant CAP', which is now not equal to $\omega_n^2/n/\alpha$. An example will serve to illustrate this point.

Consider the A-6 airplane, including a first order servo actuator lag, represented by:



At a flight condition of .88M at 20,000 feet altitude, the pitch rate transfer function to elevator inputs is expressed as:

$$\frac{\dot{\theta}(s)}{\delta e(s)} = \frac{-49.15\,(s+1.341)}{s^2+3.924s+28.6} \qquad (13)$$

where ω_n = 5.348 rad/sec

n/α = 87.7 g's/rad

$\ddot{\theta}(o)$ = -49.15 rad/sec^2

$\dot{\theta}ss$ = -2.305 rad/sec

$n_{z_{ss}}$ = -64.84 g

$\omega_n{}^2/n/\alpha$ = .759

$\ddot{\theta}(o)/n_{z_{ss}}$ = .759

This condition shows perfect agreement between $\omega_n{}^2/n/\alpha$ and CAP.

Including the servoactuator in the system definition:

$$\frac{\dot{\theta}(s)}{\delta e(s)} = \left(\frac{33.33}{s+33.33}\right)\left(\frac{-49.15\,(s+1.341)}{s^2+3.924s+28.6}\right) \qquad (14)$$

where ω_n = 5.348 rad/sec

n/α = 37.7 g's/rad

$\ddot{\theta}(o)$ = 0

$\dot{\theta}_{ss}$ = -2.305 rad/sec

$n_{z_{ss}} = .64.84$ g

$\omega_n{}^2/n/\alpha = .759$

$\ddot{\theta}(o)/n_{z_{ss}} = 0$

Obtaining the expression for $\ddot{\theta}(t)$ and evaluating it, $\ddot{\theta}_{max}$ is found to be

$$\ddot{\theta}_{max} = -38.05 \text{ rad/sec}^2$$

therefore $\ddot{\theta}_{nd} = .774$

$\ddot{\theta}_{max}/n_{z_{ss}} = .587$

For this case, there is a large discrepancy (23%) between $\omega_n{}^2/n/\alpha$ and $\ddot{\theta}_{max}/n_{z_{ss}}$. However,

$$CAP' = \frac{\omega_n^2}{n/\alpha} \ddot{\theta}_{nd} = (.759)(.774) = .587$$

is found to be identical to the ratio of maximum pitch acceleration to steady state normal acceleration. In order to interpret this condition in terms of the MIL-SPEC requirements, $\omega_n\sqrt{\ddot{\theta}_{nd}}$ must be plotted versus n/α. This point can then be correlated with boundaries of constant control anticipation parameter.

Expanding the definition of the basic system to include control system components such as feel system, actuator and/or feedback dynamics, the general pitch response to command inputs can be defined as

$$\frac{\theta(s)}{\delta_c(s)} = \frac{K_\theta(s + 1/T_{\theta_2})}{s(s^2 + 2\zeta_{sp}\omega_{n_{sp}}s + \omega_{n_{sp}}^2)} \cdot \frac{K \prod_{i=1}^{n}(s + z_i)}{\prod_{j=1}^{m}(s + P_j)} \quad (15)$$

where $n \leq m$ and z_i, p_j represent the poles and zeros introduced by the additional system components. For the general case in which $n < m$ (i.e. $\#z_i < \#p_j$)

$$\ddot{\theta}(o)_{STEP} = s\ddot{\theta}(s)\frac{1}{s}\Big|_{s\to\infty} = 0$$

$$n_{z_{ss}} = \frac{V}{g} q_{ss} = \frac{V}{g} s\dot{\theta}(s)\frac{1}{s}\Big|_{s\to\infty}$$

$$= \frac{V}{g}\frac{K_\theta(1/T_{\theta_2})}{\omega_{n_{sp}}^2}\frac{K\Pi z_i}{\Pi p_j} \qquad (16)$$

$$CAP = \ddot{\theta}(o)/n_{z_{ss}} = 0$$

Following DiFranco's development and defining on attenuation factor relating the maximum pitch acceleration with control system dynamics to that of the basic airframe yields:

$$\ddot{\theta}_{nd} = \frac{\ddot{\theta}_{max}}{\ddot{\theta}(o)_{sp}} = \frac{s + 1/T_{\theta_2}}{s^2 + 2\zeta_{sp}\omega_{n_{sp}}s + \omega_{n_{sp}}^2}\cdot\frac{K\Pi z_i}{\Pi p_j} \qquad (17)$$

substituting equations (16) and (17) into equation (7) yields

$$CAP = \frac{\ddot{\theta}_{max}}{n_{z_{ss}}\ddot{\theta}_{nd}} = \frac{\omega_{n_{sp}}^2}{n/\alpha}\frac{\Pi p_j}{K\Pi z_i} \qquad (18)$$

and defining CAP' = $\ddot{\theta}_{nd}$ CAP results in -

$$CAP' = \frac{\omega_{n_{sp}}^2}{n/\alpha}\cdot\frac{\Pi p_j}{K\Pi z_i}\ddot{\theta}_{nd} \qquad (19)$$

Equation (19) is the most general formulation of the control anticipation parameter. It reduces to Bihrle's definition for cases in which no higher order

dynamics are present and to DiFranco's formulation for cases in which only feed forward components are present. Examination of equation (19) again demonstrates that simply plotting the frequency of the dominant oscillatory root pair versus n/α for higher order systems cannot correlate directly with the requirements of MIL-F-8785.

Continuing with the example aircraft, the A-6 longitudinal control system contains washed out pitch rate feedback of the form $.12s/(s+.5)$. Including this component in the total system definition results in the following pitch angle relationship:

$$\frac{\dot{\theta}(s)}{\delta c(s)} = \frac{-1638.2(s+1.341)(s+.5)}{(s+24.67)(s^2+12.67s+46.53)(s+.415)} \qquad (20)$$

where $\omega_n = 6.821$ rad/sec

$n/\alpha = 37.7$ g's/rad

$\ddot{\theta}(o) = 0$

$\dot{\theta}ss = -2.306$ rad/sec

$n_{z_{ss}} = -64.88$ g

$\omega_n{}^2/n/\alpha = 1.234$

$\ddot{\theta}(o)/n_{z_{ss}} = 0$

Evaluating the pitch acceleration time response, $\ddot{\theta}_{max}$ is found to be equal to -33.61 rad/sec^2.

Therefore $\ddot{\theta}_{nd} = .684$

$\ddot{\theta}_{max}/n_{z_{ss}} = .518$

In this case, the discrepancy between $\omega_n{}^2/n/\alpha$ and $\ddot{\theta}_{max}/n_{z_{ss}}$ has grown to 58%. Determining CAP' by equation 19, however, yields

$$CAP' = \frac{(1.234)(.415)(24.67)}{(33.33)(.5)}(.684) = .518$$

which agrees with the value obtained from the physical interpretation of the control anticipation parameter.

CAP' BOUNDARY DETERMINATION

It has been shown that an expression can be developed relating the short-period frequency and acceleration sensitivity to the control anticipation parameter for any general aircraft/control system configuration. It has also been shown that the attenuated control anticipation parameter thus obtained is not equal to the lines of constant $\omega_n^2/n/\alpha$ defining the short period boundaries of MIL-F-8785C. Therefore, in order to utilize this approach in evaluating aircraft responses, the boundaries must be determined with respect to the attenuated response parameters.

The MIL-F-8785B and C short period requirements were established from flight tests of variable stability research vehicles. Representative maneuvering tasks were performed and the short period frequency, damping and acceleration sensitivity characteristics were evaluated as a function of pilot opinion ratings. A portion of the data utilized in that analysis was obtained from DiFranco's report, reference (c), with the assumption that the feel systems effects were negligible. DiFranco's data, first with the assumption that feel system effects are negligible and secondly with feel system effects included, are presented in Figures 5 and 6, respectively. It should be noted here that all of DiFranco's data contained level 1 damping ratios. Therefore, the pilot ratings can be assumed to reflect only the frequency/acceleration sensitivity relationship which, since there was a feel system included in the test aircraft, should be represented most accurately by CAP'.

Inclusion of feel system effects changes the boundaries primarily at the higher values of the control anticipation parameter. In this area, CAP' is appreciably less than CAP, as predicted by Figure 4. As short period frequency increases, θ_{nd} and therefore CAP', is decreased. In order to use CAP' as the correlating parameter, the specification boundaries must be modified to reflect this variation. The boundaries suggested by DiFranco are included on Figure 6. The data are repeated in Figure 7 in the format specified by MIL-F-8785B and C. From this limited amount of data it cannot be concluded which method is more advantageous. It will, however, be shown that the CAP' formulation is preferable when considering equivalent systems.

EQUIVALENT SYSTEM REPRESENTATION OF CAP'

The concept of equivalent systems, reference (e), seeks to identify an equivalent frequency and acceleration sensitivity which, as closely as possible, represents the higher order response. This is accomplished by matching the frequency response of the higher order system (on a Bode plot) with that of a first order numerator over second denominator (short period approximate transfer function) augmented by a time delay. The merits of such a matching procedure have been widely discussed and will not be repeated here. What is of interest, however, is the correlation of the resulting equivalent system parameters to the higher order system via the control anticipation parameter.

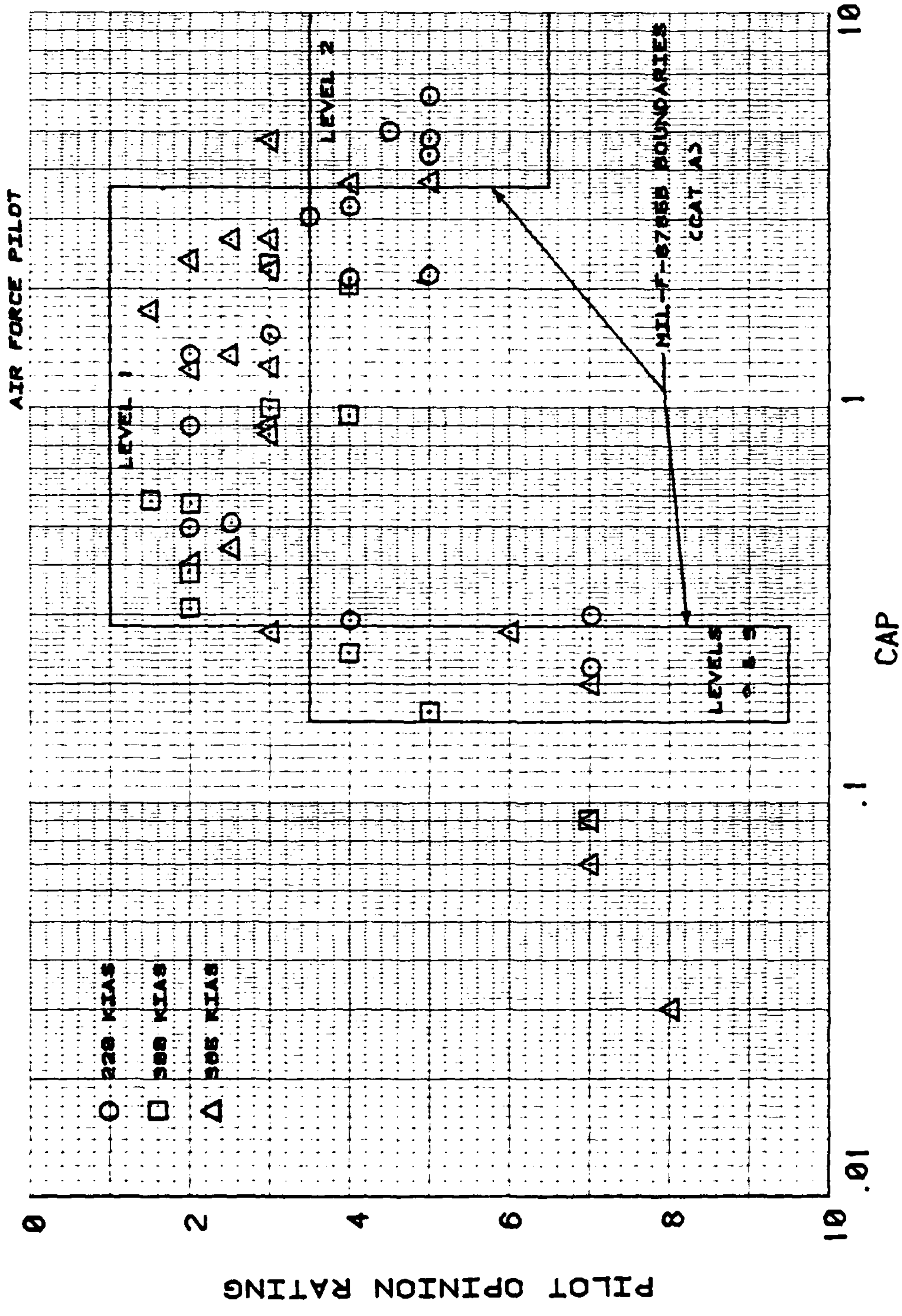


FIGURE 5. Relationship between CAP and Pilot Opinion (Reference (c) data)

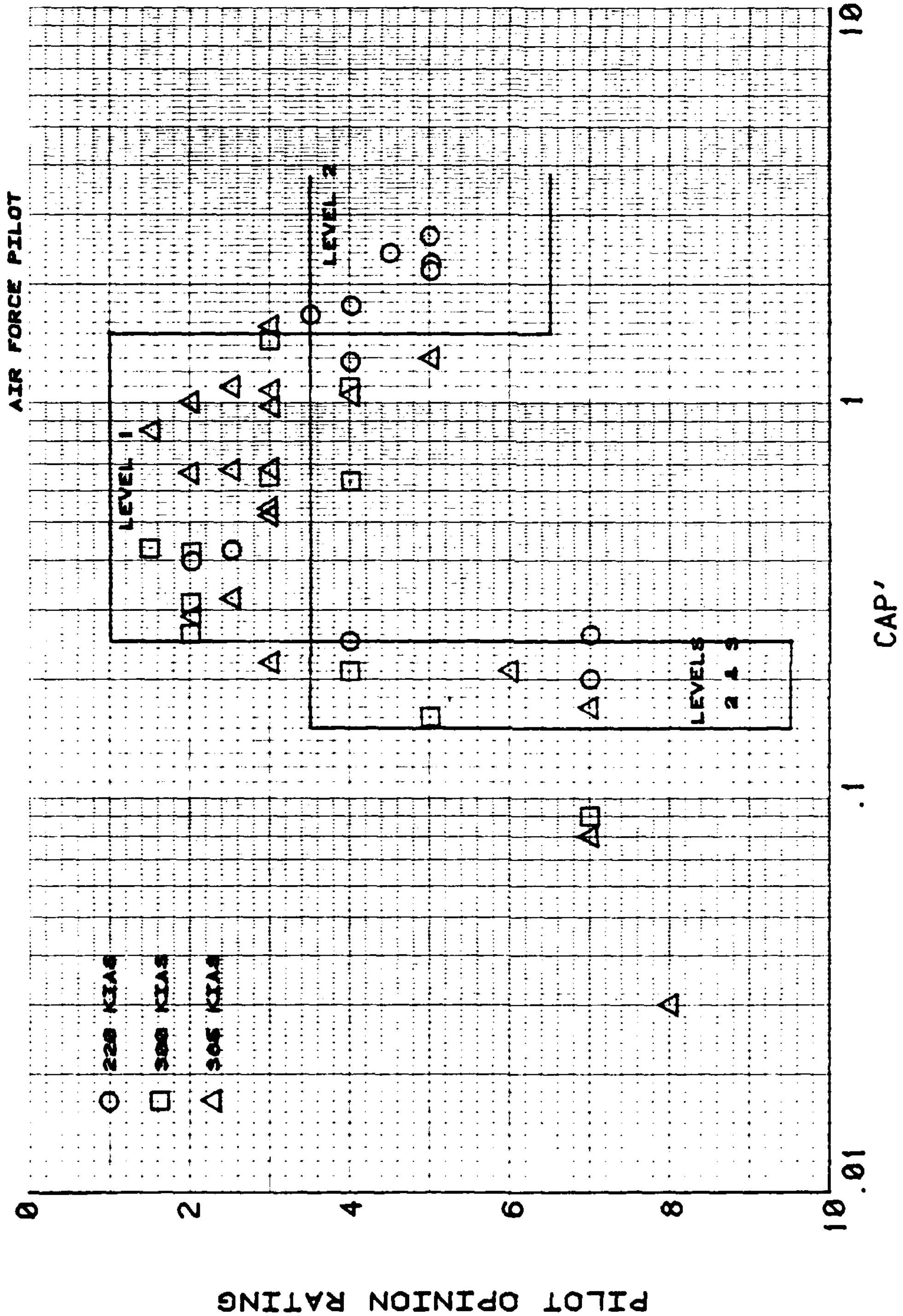


FIGURE 6. Relationship Between CAP' and Pilot Opinion

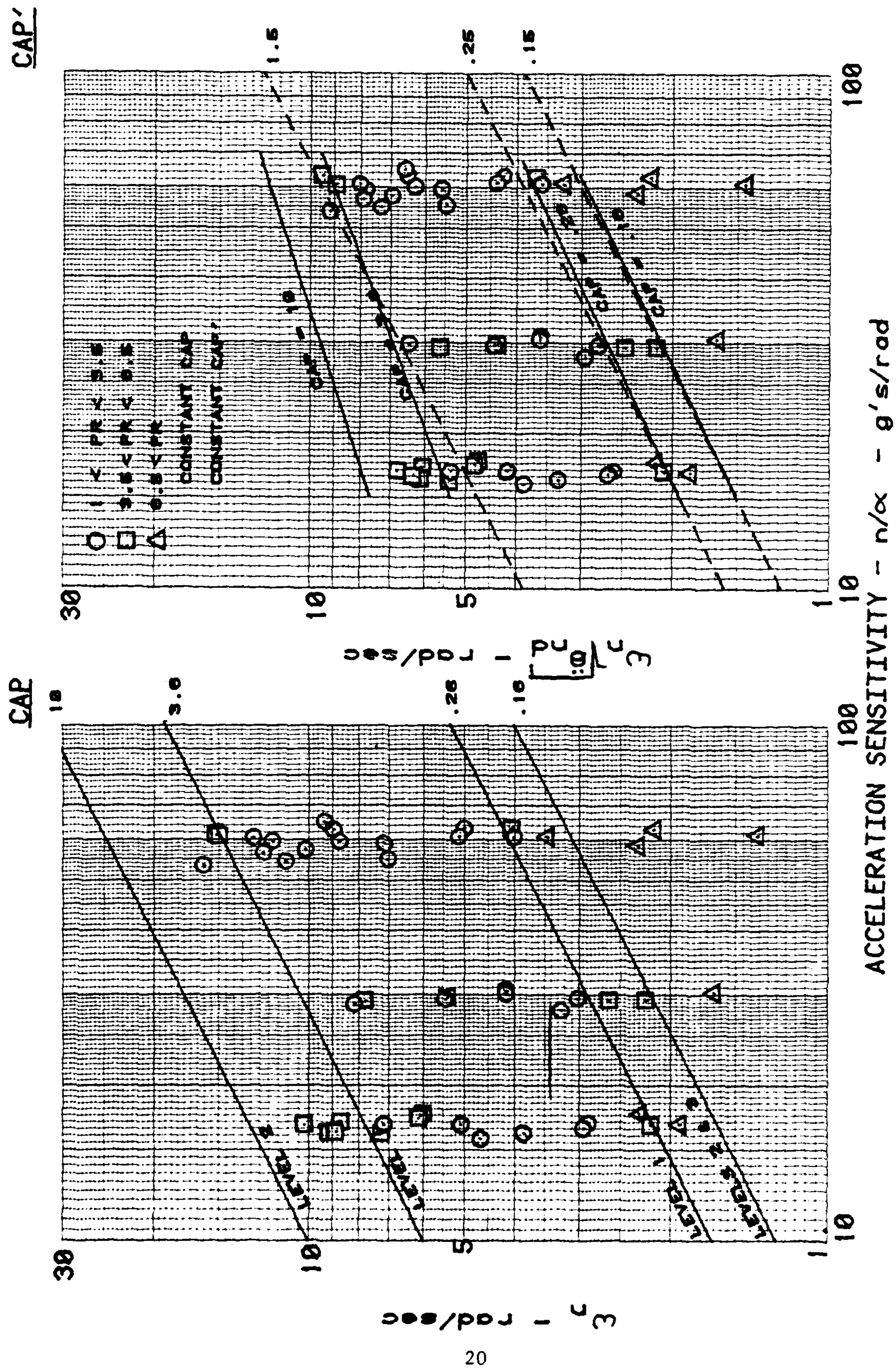


FIGURE 7. Specification Requirements Based on CAP and CAP' (Reference (c) Data)

Returning to the first example of the A-6 airplane, including servo actuator lag, the following equivalent system is obtained:

$$\frac{\dot{\theta}(s)}{\delta_c(s)} = \frac{-48.19(s+1.341)e^{-.028s}}{s^2 + 3.9s + 28.11} \qquad (21)$$

where ω_{n_e} = 5.302 rad/sec

n/α_e = 37.7 g's/rad

$\ddot{\theta}(o)$ = -48.19 rad/sec^2

$\dot{\theta}_{ss}$ = -2.298 rad/sec

$n_{z_{ss}}$ = -64.64 g's

$(\omega_n{}^2/n/\alpha)_e = CAP_e = .746$

$\ddot{\theta}(o)/n_{z_{ss}} = .746$

There is consistency within the $\omega_n{}^2/n/\alpha$ and CAP parameters for the equivalent model (as would be expected from the definition of CAP). However, the control anticipation parameter previously developed for the higher order system is considerably less (CAP' = .587). Although there is excellent agreement between the overall high and low order system pitch rate responses, (Figure 8), there is a noticeable difference in the initial portion of those responses. As in the case with and without feed forward terms, there appears to be an attenuation of the maximum pitch acceleration response between the lower and higher order systems. Constructing an attenuation factor of the form

$$\ddot{\theta}_{nd_e} = \frac{\ddot{\theta}_{max\ HOS}}{\ddot{\theta}_{LOS\,(t=t_d)}} \qquad (22)$$

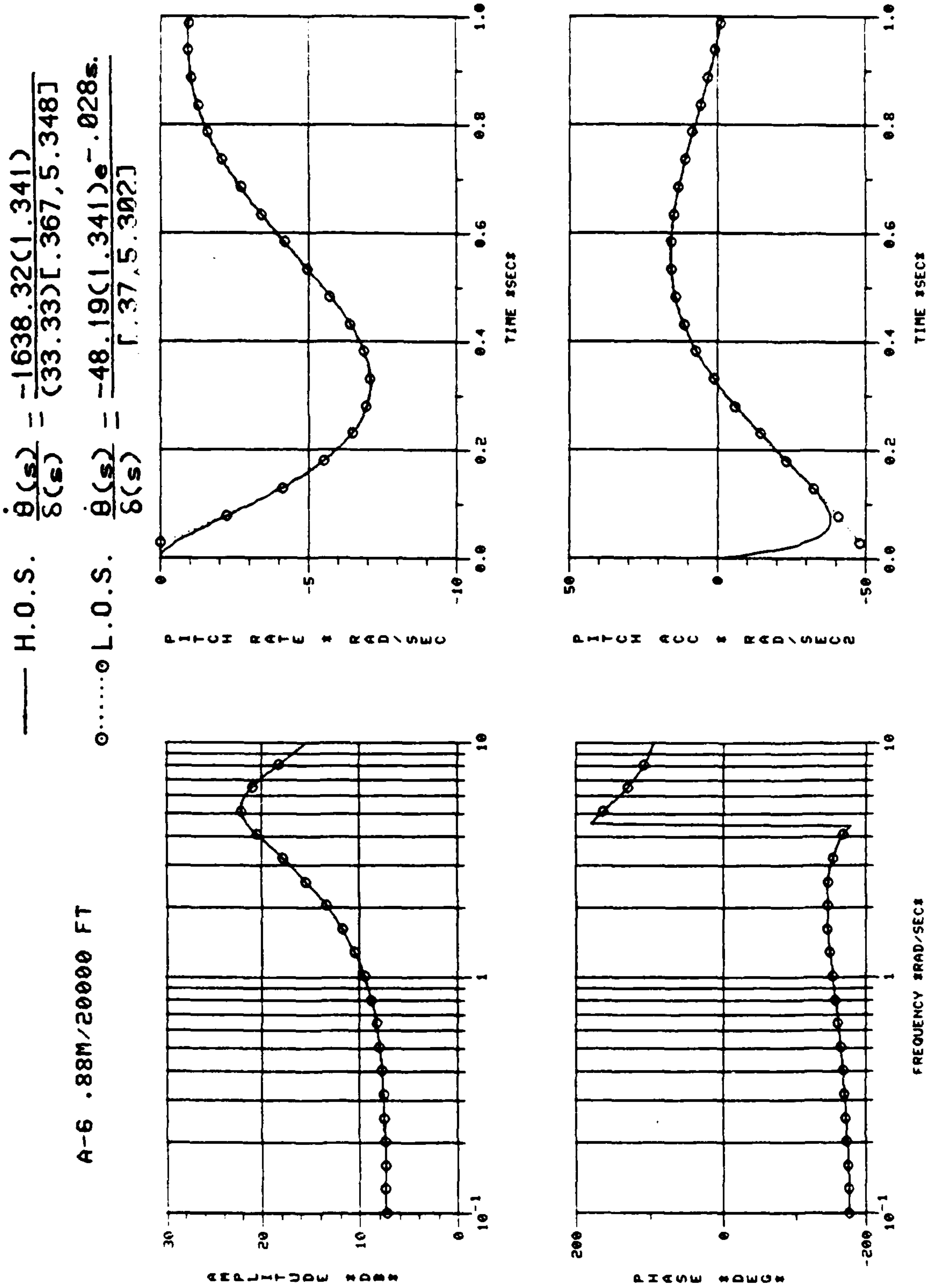


FIGURE 8. Equivalent System Comparison - A-6 Airplane

and multiplying this by CAP_e yields

$$CAP'_e = CAP_e \ddot{\theta}_{nd_e} = \left(\frac{\omega^2_{n_{sp}}}{n/\alpha}\right)_e \frac{\ddot{\theta}_{max\ HOS}}{\ddot{\theta}_{LOS}(t=t_d)} \qquad (23)$$

For the A-6 example -

$$CAP'_e = (.746)(.790) = .589$$

which is within .5% of CAP' for the higher order system. Therefore, a correlation between the higher order and an equivalent lower order system can be established by plotting $\omega_n \sqrt{\theta nd}$ versus n/α for both systems.

The case of the A-6 with washed out pitch rate feedback yields the following equivalent system:

$$\frac{\dot{\theta}(s)}{\delta c(s)} = \frac{-75.26(s+1.341)e^{-.042s}}{s^2 + 15.23s + 47.59}$$

where ω_{n_e} = 6.9 rad/sec

n/α_e = 37.7 g's/rad

$\ddot{\theta}(o)$ = -75.26 rad/sec^2

$\dot{\theta}_{ss}$ = -2.12 rad/sec

$n_{z_{ss}}$ = -59.65 g's

$$(\omega_n{}^2/n/\alpha)_e = 1.263$$

$$\ddot{\theta}(o)/n_{z_{ss}} = 1.262$$

$$\ddot{\theta}nd_e = .447$$

$$CAP'_e = .564$$

Again, CAP'_e is found to provide very good correlation with CAP' (.518) while $\omega_n{}^2/n/\alpha$ is considerably different and provides little information about the high order system what remains to be established, is whether or not the attenuated control anticipation parameters thus defined can be correlated with pilot opinion.

FLIGHT TEST CORRELATION OF CAP'

In order to evaluate the acceptability of utilizing the control anticipation parameters for specifying the short period dynamics, two extensive higher order system flight research programs were analyzed. Both flight programs (references (f) and (g)) were conducted by the CALSPAN corporation on the NT-33 aircraft. The first program, referred to as NEAL-SMITH, investigated the effects of adding lead/lag and pure lag control system components to basic aircraft dynamics in maneuvering flight. The second program, referred to as LAHOS, investigated the effects of adding lead/lag, pure lag and second order control system components to the basic airframe under power approach flight conditions. Details of the configurations investigated are contained in Tables I and II, respectively.

Lower order equivalent systems were determined for both programs using the McAIR equivalent system fitting routine, reference (h). Equivalent systems for the NEAL-SMITH data were determined by NAVAIRDEVCEN while the LAHOS equivalents were obtained from reference (i). In addition, the maximum pitch acceleration was obtained from time responses for each of the configurations. The resulting high and low order response parameters are presented in Tables III and IV.

Before comparing the data against the specification requirements, it must be determined whether CAP or CAP' is the most appropriate parameter. In order to do this, CAP' was plotted against both CAP_e and CAP'_e as shown in Figures 9 and 10. The short period approximate control anticipation parameter, CAP_e, exhibits large variations from the higher order system's CAP'. Including the attenuation factor between the high and low order systems considerably improves the correlation as shown by CAP' versus CAP'_e. Based on these results, and the fact that CAP' is directly related to the aircraft's time response, CAP' was chosen as the correlating parameter.

Figures 9 and 10 also provide additional information concerning the effects of freeing $L\alpha$ in the equivalent system matching process. The CAP_e - CAP' correlation is improved by freeing $L\alpha$ at high values of CAP' (lead/lag cases) while at low values of CAP' (medium frequency lag cases), it is degraded. This inconsistent variation of CAP_e further points out the problems associated with freeing $L\alpha$ in the equivalent system matching process, as discussed in the literature (e.g., references (e) and (i)).

TABLE I

NEAL-SMITH DATA CONFIGURATION SUMMARY

(Table from reference (f))

CONTROL SYSTEM CHARACTERISTICS			SHORT PERIOD CHARACTERISTICS							
			n/α = 18.5 g/RAD, V_{ind} = 250 KT, $1/\tau_{\theta_2}$ = 1.25 SEC^{-1}					n/α = 50 g/RAD, V_{ind} = 350 KT, $1/\tau_{\theta_2}$ = 2.4 SEC^{-1}		
			ω_{SP}/ζ_{SP}					ω_{SP}/ζ_{SP}		
$1/\tau_1$	$1/\tau_2$	ω_3	2.2/.69	4.9/.70	9.7/.63	5.0/.28	5.1/.18	3.4/.67	7.3/.73	16.5/.69
0.5	2	63	1A							
0.8	3.3							6A		
2	5		1B	2A						
3.3	8							6B	7A	
5	12			2C						
8	19	↓							7B	
∞	∞	75	1D	2D	3A	4A	5A	6C	7C	8A
	19	63							7D	8B
	12			2E	3B	4B	5B			
	8							6D	7E	8C
	5		1E	2F	3C	4C	5C			
	3.3							6E	7F	8D
	2		1F	2H	3D	4D	5D		7G	
	0.8							6F	7H	8E
↓	0.5	↓	1G	2J	3E	4E	5E			
2	5	16	1C	2B						
∞	5			2G						
↓	2	↓		2I						

NOTE: (1) Numbers/Letters Indicate Configurations Simulated

(2) ζ_3 =.75 for ω_3 = 63, 16; ζ_3 =.67 for ω_3 =75

TABLE II

LAHOS DATA CONFIGURATION SUMMARY

(Table from reference (g))

CONTROL SYSTEM DYNAMICS				SHORT PERIOD DYNAMICS (Nominal) V_{ind} = 120 Kt; n_z/α = 4.5 g/rad; τ_{θ_2} = 1.4 sec				
				ω_{sp}/ζ_{sp}				
τ_1	τ_2	ω_3/ζ_3	ω_4/ζ_4	1.0/.74	2.3/.57	2.2/.25	2.0/1.06	3.9/.54
0.4	0.1	-	-	1-A	2-A			
0.3	0.1	-	-	1-B				
0.2	0.1	-	-	1-C	2-C	3-C	4-C	
0	0	-	-	1-1	2-1	3-1(3-0)*	4-1(4-0)*	5-1
	0.1	-	-	1-2	2-2	3-2		
	0.25	-	-	1-3	2-3	3-3	4-3	5-3
	0.5	-	-	1-4	2-4		4-4	5-4
	1.0	-	-					5-5
	0	16/.7	-	1-6	2-6	3-6	4-6	5-6
		12/.7	-		2-7	3-7	4-7	5-7
		9/.7	-	1-8				
		6/.7	-		2-9			
		4/.7	-		2-10		4-10	
0	0	16/.93	16/.38	1-11	2-11		4-11	5-11

*ω_{sp}/ζ_{sp} for Configuration 3-0 is 2.1/.14; for Configuration 4-0, 2.1/1.23

CONFIGURATION	CONTROL SYSTEM DYNAMICS	ω_{sp}/ζ_{sp}
6-1 (YF-17 Original)	$\dfrac{(.5s+1)(.43s+1)}{(.2s+1)(1.1s+1)\left(\frac{s^2}{4^2}+\frac{2(.7)}{4}s+1\right)}$	1.9/.65
6-2 (YF-17 Modified)	$\dfrac{(.5s+1)(.43s+1)(.065+1)}{(.2s+1)(.1s+1)(1.1s+1)}$	1.9/.65

NOTES:
- First number indicates base aircraft configuration simulated; second number or letter identifies control system dynamics; letters for control system lead; numbers for lag.
- Total configuration dynamic model includes feel system and actuator dynamics

TABLE III

PARAMETER TABULATION - NEAL-SMITH DATA

CASE	HIGH ORDER SYSTEM $\ddot{\theta}_{max}$	$n_{z_{ss}}$	CAP'	LOW ORDER SYSTEM - L_α FIXED ω_{n_e}	ζ_e	t_d	CAP_e	$\ddot{\theta}_{\alpha_e}$	CAP'_e	MIS-MATCH	LOW ORDER SYSTEM - L_α FREE n/α	ω_{n_e}	ζ_e	t_d	CAP_e	$\ddot{\theta}_{\alpha_e}$	CAP'_e	MIS-MATCH	PILOT RATING M	W
1A	13.88	14.80	.94	3.13	.39	-.004	.53	1.27	.67	123.4	6.36	2.54	.66	.02	1.01	.94	.95	.8	6,4	5
1B	8.25		.56	3.10	.69	.009	.52	1.03	.54	5.1									3.5	3
1C	5.78		.39	3.03	.67	.079	.50	.76	.38	3.9									5,3.5	4
1D	3.86		.26	2.2	.69	.018	.26	1.0	.26	.01									5,4.5	3,4
1E	2.07		.14	1.8	.58	.129	.18	.84	.11	21.6	52.1	2.53	.48	.104	.12	1.10	.14	7.2	6	-
1F	1.35		.091	1.38	.55	.161	.10	.98	.10	73.4	203.4	2.48	.57	.074	.03	2.94	.089	2.3	8	8
1G	.52		.035	78	.74	.184	.033		.041	150.5	1505.2	1.55	1.07	.047	.002	23.9	.038	13.1	8.5	8.5
2A	36.16		2.44	5.84	.42	-.008	1.84	1.17	2.25	16.1	13.62	5.89	.55	.008	2.55	.98	2.49	2.2	4.5	4
2B	20.6		1.39	5.67	.42	.059	1.74	.75	1.30	13.5	13.91	5.67	.53	.073	2.31	.61	1.42	1.5	6,6	4,5
2C	31.49		2.13	6.13	.64	.003	2.03	1.03	2.10	1.2									3	-
2D	17.01		1.15	4.9	.70	.018	1.30	.88	1.15	.01									3,25	2.5
2E	9.39		.63	4.41	.68	.080	1.05	.61	.64	.9									4	-
2F	6.03		.41	3.59	.68	.107	.70	.60	.42	5.5									3	-
2G	5.64		.38	3.50	.66	.176	.66	.59	.39	9.3									7	-
2H	3.25		.22	2.57	.8	.126	.36	.64	.23	4.6									5,6	5.5
2I	3.17		.21	2.52	.78	.196	.34	.65	.22	21.1	82.58	4.04	.49	.159	.20	1.05	.21	6.7	8	8
2J	1.01		.068	1.37	1.36	.139	.10	.70	.071	25.8	9.77	.95	1.48	.135	.092	.73	.067	20.8	6	6
4A	19.85		1.34	4.99	.28	.018	1.35	1.0	1.35	.01									5.5	5
4B	12.89		.87	4.79	.29	.09	1.24	.71	.88	2.8									-	7
4C	8.74		.59	4.32	.35	.133	1.01	.62	.63	23.8	25.75	4.51	.26	.119	.79	.73	.58	11.8	8.5	-
4D	4.91		.33	3.48	.58	.169	.65	.56	.36	79.5	79.7	4.61	.23	.111	.27	1.14	.31	13.6	8,9	-
4E	1.56		.11	2.06	1.51	.197	.23	.52	.12	152.4	6.81	1.14	2.17	.195	.19	.53	.10	131.4	7.5	-
5A	21.22		1.43	51	.18	.018	1.41	1.02	1.43	.01									7	5,6
5B	14.45		.98	4.96	.19	.092	1.33	.75	.99	3.9									-	7
5C	9.95		.67	4.61	.24	.140	1.15	.63	.73	35.8	26.8	4.77	.17	.124	.85	.77	.65	16.6	9	7
5D	5.64		.38	3.87	.48	.182	.81	.54	.44	129.1	82.7	4.86	.15	.113	.29	1.25	.36	17.6	8.5,9	9
5E	1.8		.12	2.38	1.54	.215	.31	.46	.14	254.	6.92	1.24	2.50	.215	.26	.47	.12	226.7	8	8
6A	17.23	20.83	.83	4.53	.32	-.018	.41	1.49	.61	122.8	15.41	3.74	.65	.019	.91	.90	.82	.3	5	6
6B	9.28		.45	4.48	.64	.004	.40	1.08	.43	3.3									25,1	4
6C	4.77		.23	3.4	.67	.018	.23	.98	.23	.01									4	5
6D	2.81		.14	2.95	.62	.101	.17	.79	.13	4.8									5.5	-
6E	1.94		.093	2.33	.61	.132	.11	.88	.097	22.6	313.9	3.58	.59	.069	.041	2.23	.091	.4	8.5	7
6F	.76		.036	1.33	.85	.158	.035	1.12	.039	61.3	860.3	2.25	1.13	.067	.006	6.33	.038	11.2	8	8.5,10
7A	35.8		1.72	7.84	.43	-.014	1.23	1.35	1.66	5.7									5,4	2
7B	31		1.49	8.54	.66	.003	1.46	1.01	1.48	.2									3	-
7C	18.49		.89	7.29	.72	.018	1.06	.83	.88	.01									3,3	4,1.5
7D	11.21		.54	6.79	.73	.061	.92	.59	.54	1									5.5	-
7E	7.45		.36	5.73	.75	.083	.66	.54	.36	7									6	5
7F	4.22		.20	4.24	.87	.1	.36	.56	.20	2.6									3,4,4	7,7
7G	2.85		.14	3.44	1.02	.105	.24	.58	.14	3.9									5	6
7H	.84		.04	1.82	1.84	.114	.066	.62	.041	6.2									-	5
8A	72.2		3.47	16.51	.68	.018	5.45	.64	3.49	0									5	4
8B	34.5		1.66	13.46	.73	.051	3.62	.46	1.67	.4									3.5	-
8C	20.3		.97	10.32	.87	.059	2.13	.46	.99	1.7									3.5	3
8D	10.1		.48	9.13	1.52	.076	1.67	.29	.49	.1									2	4
8E	2.76		.13	5.09	3.22	.083	.52	.26	.13	.1									2.5	5

TABLE IV - PARAMETER TABULATION - LAHOS DATA

CASE	HIGH ORDER SYSTEM $\ddot{\theta}_{max}$	HIGH ORDER SYSTEM $n_{z_{ss}}$	HIGH ORDER SYSTEM CAP'	LOW ORDER SYSTEM - L_α FIXED ω_{n_e}*	ζ_e*	t_d*	CAP_e	$\ddot{\theta}_{\alpha d_e}$	CAP'_e	MIS-MATCH*	LOW ORDER SYSTEM - L_α FREE n/α*	ω_{n_e}*	ζ_e*	t_d*	CAP_e	$\ddot{\theta}_{\alpha d_e}$	CAP'_e	MIS-MATCH*	PILOT RATING* A	PILOT RATING* B
1-A	3.78	6.29	.60	1.50	1.18	.028	.50	1.1	.55	26.3	1.36	.87	1.77	.028	.56	1.12	.63	21.0	6	-
1-B	2.98		.47	1.30	1.04	.026	.38	1.17	.44	23.5	1.66	.83	1.41	.028	.42	1.15	.48	18.8	5	-
1-C	2.17		.34	1.13	.88	.035	.28	1.16	.32	11.7	2.41	.86	1.04	.037	.31	1.13	.35	8.9	4	4
1-1	1.44		.23	1.02	.74	.067	.22	1.02	.22	.2									4	4
1-2	1.14		.18	.96	.69	.147	.20	.90	.18	6.2									5	-
1-3	.92		.15	.84	.57	.197	.16	1.01	.16	59.6	40.31	1.75	.71	.143	.076	1.78	.14	11.8	9	10
1-4	.73		.12	.73	.49	.228	.72	1.16	.14	161.8	75.6	1.48	.69	.127	.029	3.77	.11	6.4	10	-
1-6	1.34		.21	1.00	.74	.161	.22	.95	.21	.3									5	-
1-8	1.21		.19	.97	.70	.234	.21	.94	.20	13.1	6.79	1.15	.67	.230	.20	.98	.19	11.8	-	8
1-11	1.41		.22	1.00	.75	.238	.22	1.0	.22	.4									-	9
2-A	18.69		2.97	3.48	.65	.034	2.69	1.02	2.75	18.8	3.36	3.34	.78	.043	3.32	.89	2.95	8.0	4	6
2-C	10.66		1.69	2.69	.64	.043	1.61	1.02	1.63	5.9									1.5, 4 3, 1.5	-
2-1	6.90		1.10	2.30	.57	.067	1.18	.93	1.09	.2									2	2
2-2	5.04		.80	2.16	.53	.143	1.04	.78	.81	4.3									4.5	4
2-3	3.48		.55	1.84	.49	.186	.75	.79	.59	36.4	7.42	2.11	.38	.174	.60	.89	.53	22.5	6	-
2-4	2.41		.38	1.50	.49	.210	.50	.83	.42	88.7	18.07	2.24	.32	.173	.28	1.25	.35	32.9	9	-
2-6	6.07		.96	2.31	.57	.161	1.19	.81	.96	.3									5	-
2-7	5.55		.88	2.28	.56	.193	1.16	.77	.89	2.3									7	6
2-9	5.15		.82	2.00	.46	.285	.89	.98	.87	67.2	7.08	2.25	.36	.274	.72	1.11	.80	54.0	-	10
2-10	3.25		.52	1.71	.39	.332	.65	.90	.58	202.4	34.36	2.71	.22	.261	.21	1.96	.41	114.6	10	-
2-11	6.24		.99	2.33	.58	.240	1.21	.82	.99	.3									-	8
3-C	10.68		1.70	2.38	.27	.030	1.26	1.26	1.59	18.2	3.71	2.32	.31	.035	1.45	1.20	1.74	11.1	2	5
3-0	6.71		1.07	2.10	.14	.067	.98	1.08	1.06	.2									5,4	-
3-1	7.06		1.12	2.20	.25	.067	1.08	1.04	1.11	.2									5,4	7
3-2	6.38		1.01	2.13	.24	.143	1.01	1.03	1.04	7.4									7	-
3-3	4.19		.67	1.95	.23	.202	.85	.86	.73	74.2	7.39	2.12	.17	.187	.61	1.04	.63	42.4	10	-
3-6	6.56		1.04	2.21	.25	.161	1.09	.95	1.04	.3									7	6
3-7	6.17		.98	2.19	.25	.181	1.07	.92	.99	2.4									8	-
4-C	7.4		1.18	2.58	1.30	.057	1.48	.78	1.16	.9									3	3
4-0	4.94		.79	2.10	1.23	.067	.98	.80	.78	.2									6	-
4-1	4.74		.75	2.00	1.06	.067	.89	.84	.75	.2									2	-
4-3	2.18		.35	1.46	.81	.172	.47	.76	.36	18.6	11.02	2.07	.61	.159	.39	.86	.34	10.0	5,7	8
4-4	1.46		.23	1.15	.72	.190	.29	.83	.24	41.8	48.14	2.58	.65	.135	.14	1.58	.22	7.1	7	6
4-6	4.00		.64	2.01	1.06	.161	.90	.7	.63	.3									4	-
4-7	3.59		.57	1.97	1.03	.181	.86	.66	.57	2.1									3	-
4-10	1.97		.31	1.33	.64	.314	.39	.88	.34	151.1	81.59	2.88	.44	.218	.10	2.85	.28	24.8	9	-
4-11	4.06		.65	2.03	1.07	.240	.92	.70	.64	.3									8	-
5-1	17.54		2.79	3.90	.54	.067	3.38	.82	2.77	.2									7	5
5-3	7.51		1.19	2.95	.54	.174	1.93	.64	1.24	19.1	5.80	3.10	.45	.167	1.66	.71	1.17	13.2	4,5,8	6
5-4	4.73		.75	2.35	.63	.193	1.23	.65	.80	42.4	7.62	2.72	.46	.181	.92	.78	.72	25.4	6	-
5-5	2.75		.44	1.77	.83	.206	.70	.68	.47	64.8	45.18	3.58	.41	.142	.28	1.42	.40	10.3	7	-
5-6	14.37		2.28	3.90	.52	.159	3.38	.67	2.27	.4									-	6
5-7	12.66		2.01	3.82	.52	.190	3.24	.62	2.02	1.9									6	-
5-11	14.29		2.27	3.95	.54	.240	3.47	.65	2.26	.3									7	-
6-1	1.62		.26	1.30	.56	.321	.38	.78	.30	181.7	50.63	2.53	.39	.240	.13	1.88	.24	37.5	10	-
6-2	3.51		.56	1.74	.78	.084	.67	.85	.57	1.7									2	-

* REFERENCE (1) DATA

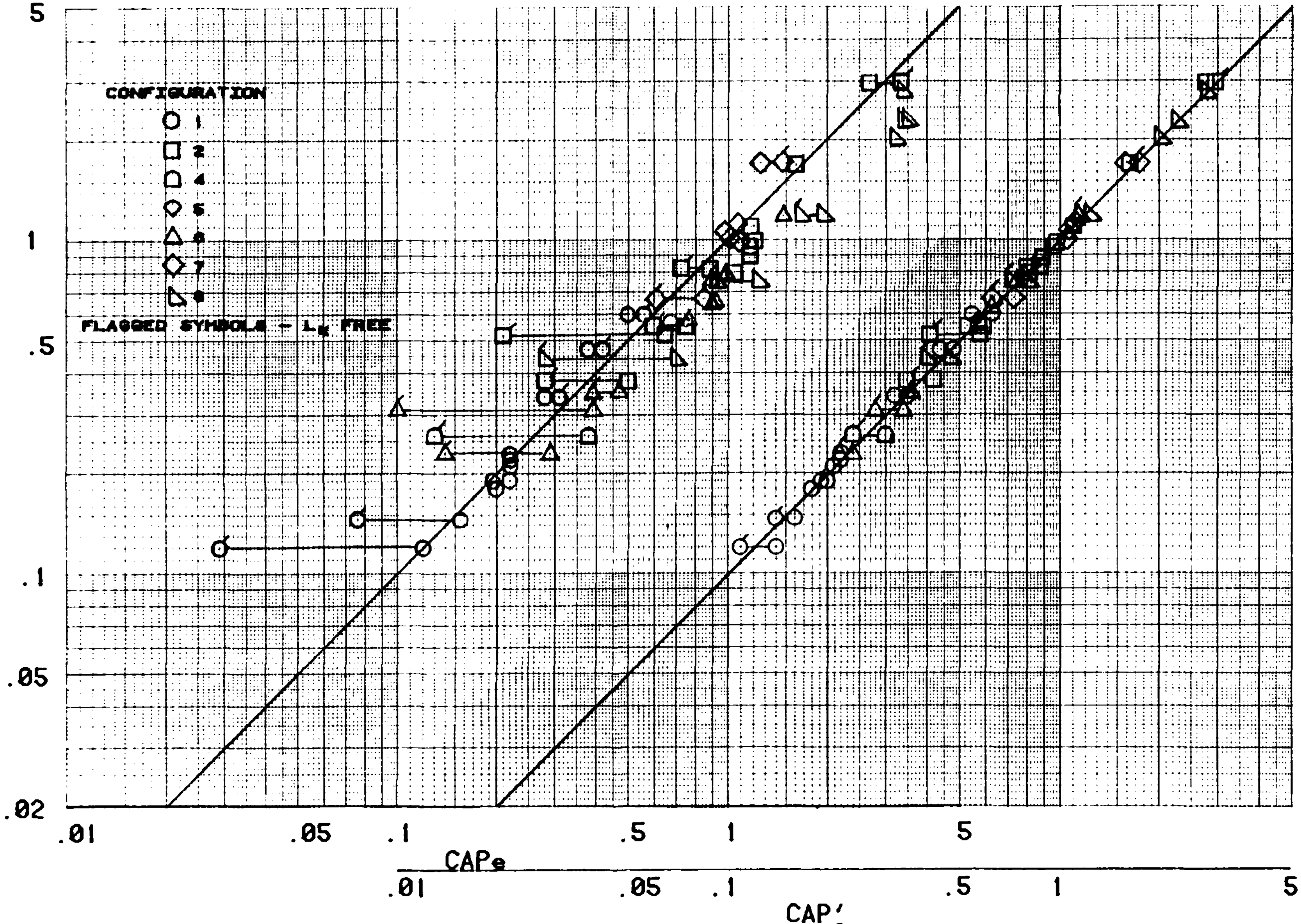


FIGURE 9. Control Anticipation Parameter Comparison - NEAL-SMITH Data

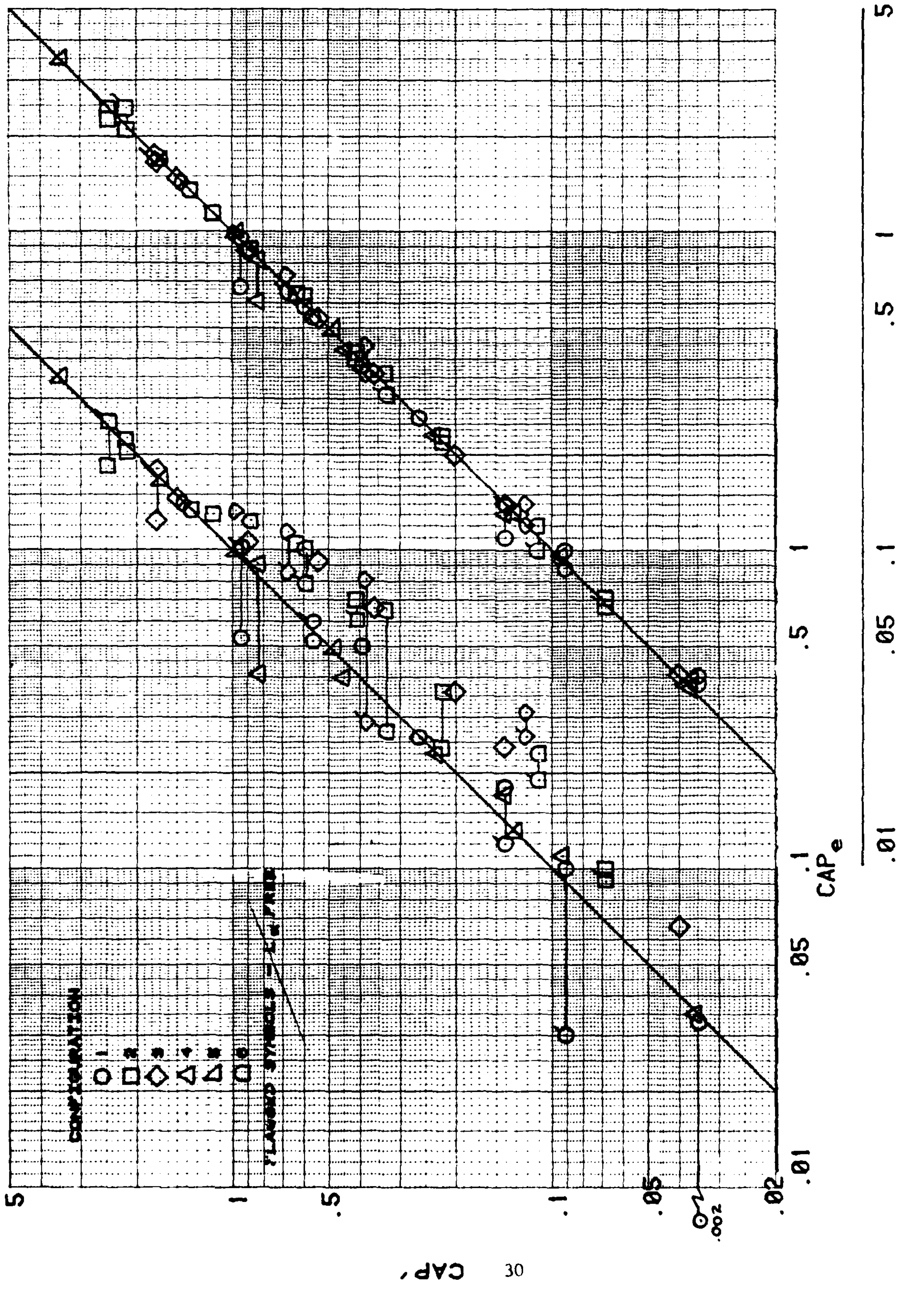


FIGURE 10. Control Anticipation Parameter Comparison - LAHOS Data

Inspection of Tables III and IV indicates large variations in pilot ratings for configurations possessing satisfactory, i.e., - Level 1, values of CAP'. For example, LAHOS cases 2-1 through 2-11 all have values of CAP' between .25 and 1.4 yet their pilot ratings range from 2 to 10. The equivalent damping ratios are all acceptable ($.35 < \zeta_e < 1.3$) and therefore should not contribute to the variation in pilot rating. The parameter which has not yet been considered in this analysis is the equivalent time delay. This parameter is a result of the matching process. It is used to account for the high frequency phase lags not included in the first/second order short period approximation. The LAHOS configuration 2 time delays vary from .067 to .332 seconds, spanning the range of acceptable/unacceptable values specified in MIL-F-8785C. Using only those configurations which exhibit level 1 damping ratios, CAP' was plotted against time delay for both the NEAL-SMITH and LAHOS data as shown in Figures 11 and 12, respectively. Simultaneously applying the CAP' boundaries shown in Figure 6 and the time delay requirements of MIL-F-8785C results in regions of acceptable/unacceptable flying qualities characteristics which agree reasonably well with the pilot opinion data. The primary discrepancy for the NEAL-SMITH data occurs in the region:

$$.25 < CAP' < .6$$
$$.05 < t_d < .1$$

The level 1 boundaries could be modified to exclude these data paints, however, the boundaries would then be in disagreement with DiFranco's data (Figure 6). Determining equivalent systems for DiFranco's data results in time delays of .082 - .085 seconds. Plotting that data as a function of CAP' versus time delay yields a large number of pilot ratings of 2 and 3 in the region in question. The LAHOS data shown even better correlation than that obtained from the NEAL-SMITH data; the major discrepancy again occuring at the lower values of CAP' in the level 1 region.

An alternate method of analyzing augmented aircraft longitudinal dynamics has been proposed by Systems Technology, Incorporated (reference (i)). It consists of plotting the bandwidth of the higher order system (based on either gain or phase margin) versus the equivalent time delay. STI's results for the NEAL-SMITH and LAHOS data are presented in Figures 13 and 14, respectively. The same data points which do not correlate with the CAP'/t_d boundaries are the ones which determine the level 1 bandwidth boundaries. Since there are only a limited number of data points which either (1) do not correlate with existing boundaries or (2) are being used to define new boundaries, it is recommended that additional data be acquired and/or analyzed. This analysis should include a determination of the relationship between CAP' and bandwidth.

The NEAL-SMITH data of Figure 11 also indicates that the level 2 boundary may be extended to lower values of CAP' and that it may be possible to define different minimum CAP' boundaries for level 2 and 3 flying qualities.

The data of Figures 11 and 12 also indicate the influence of damping ratio on pilot opinion for the tasks performed. In all cases, the reduction of equivalent damping ratio below the minimum level 1 boundary ($\zeta_e < .35$) results in at least a one level degradation of pilot opinion (i.e., level 1 is degraded to level 2 and level 2 to level 3). However, for equivalent damping ratio greater then the maximum level 1 requirement ($\zeta_e > 1.3$), an improvement in pilot ratings is indicated. Again, further analysis is recommended since only a minimum number of data points are available to support this observation.

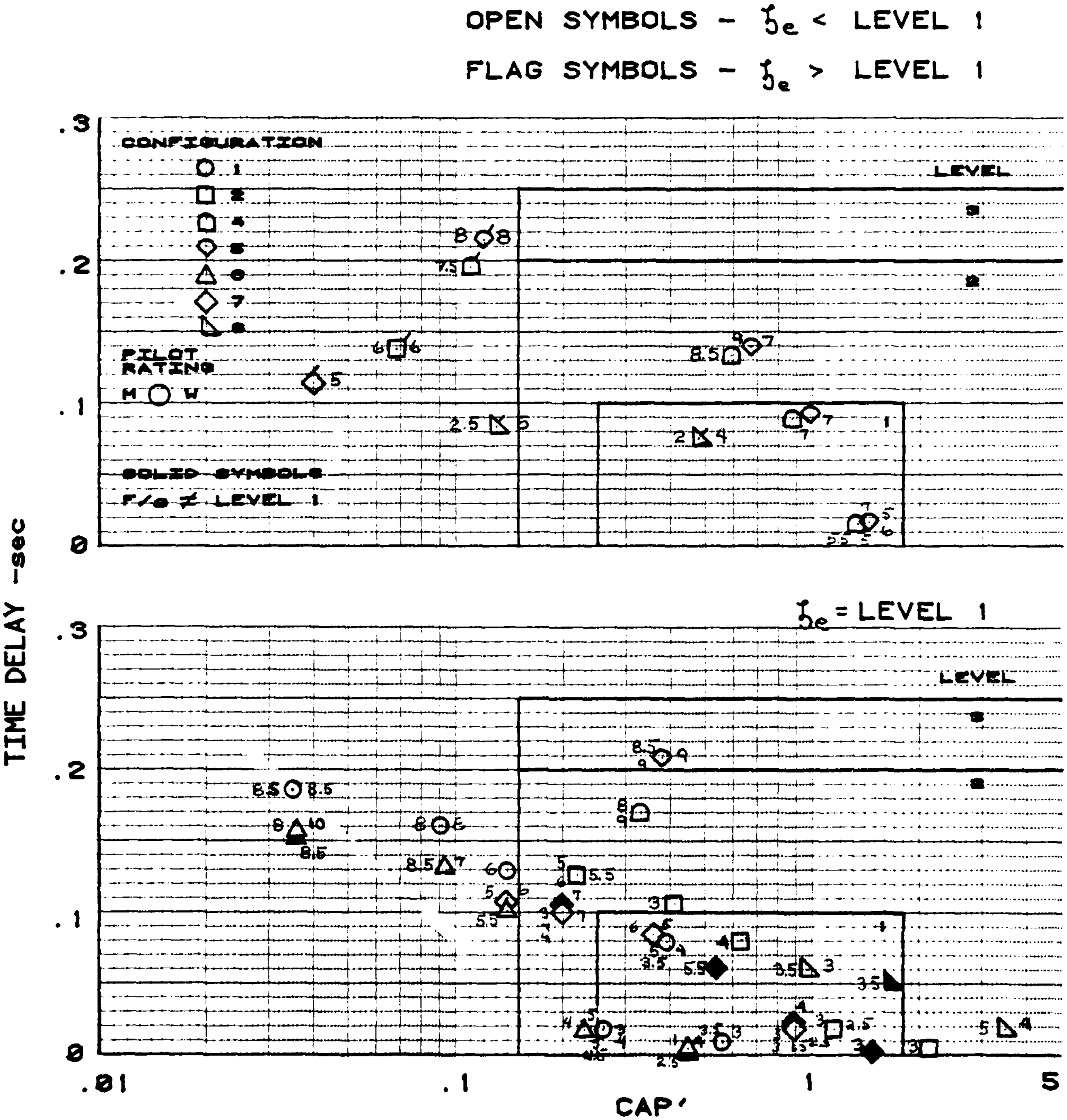


FIGURE 11. Time Delay versus CAP' - NEAL-SMITH Data

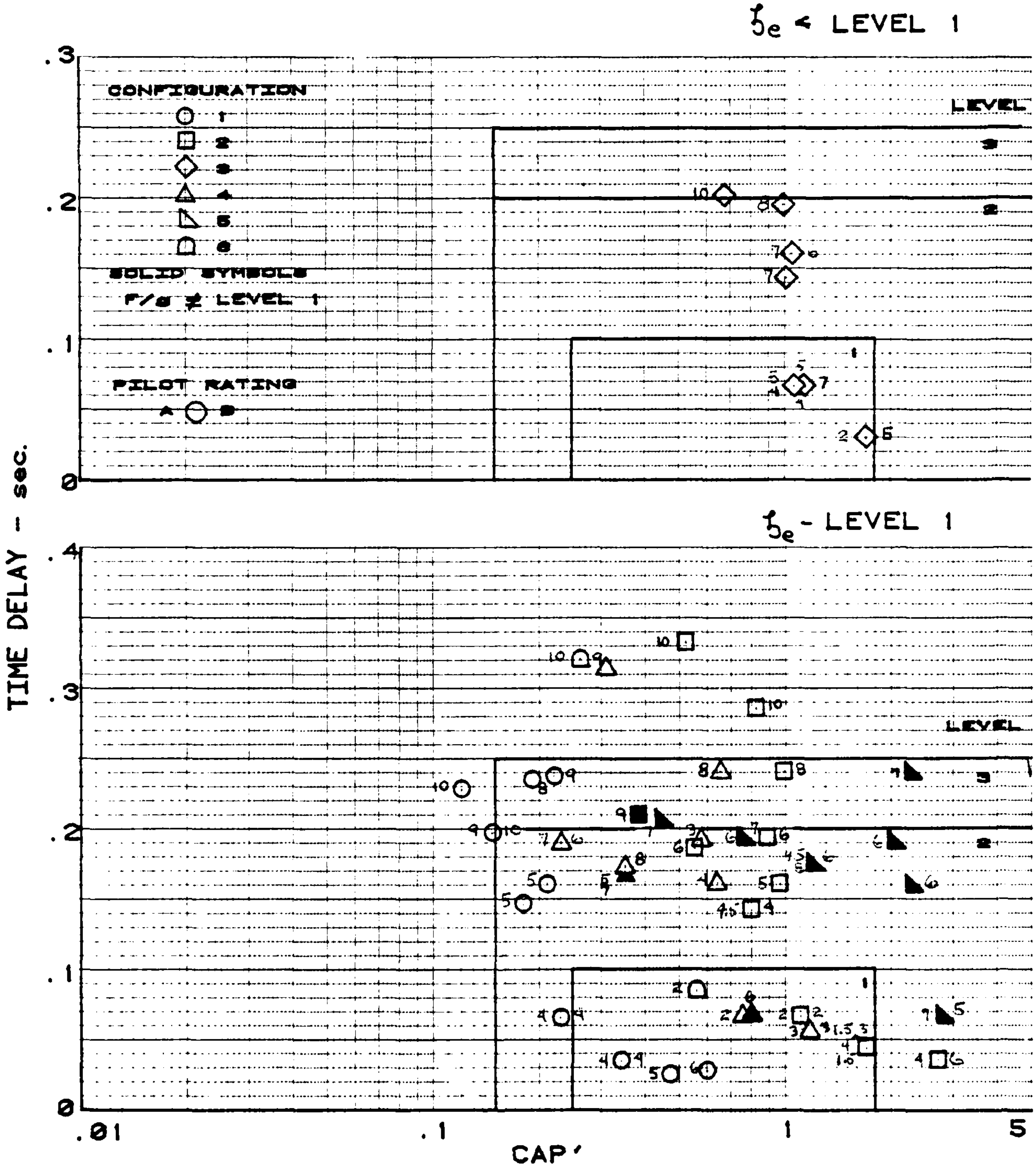


FIGURE 12. Time Delay versus CAP' - LAHOS Data

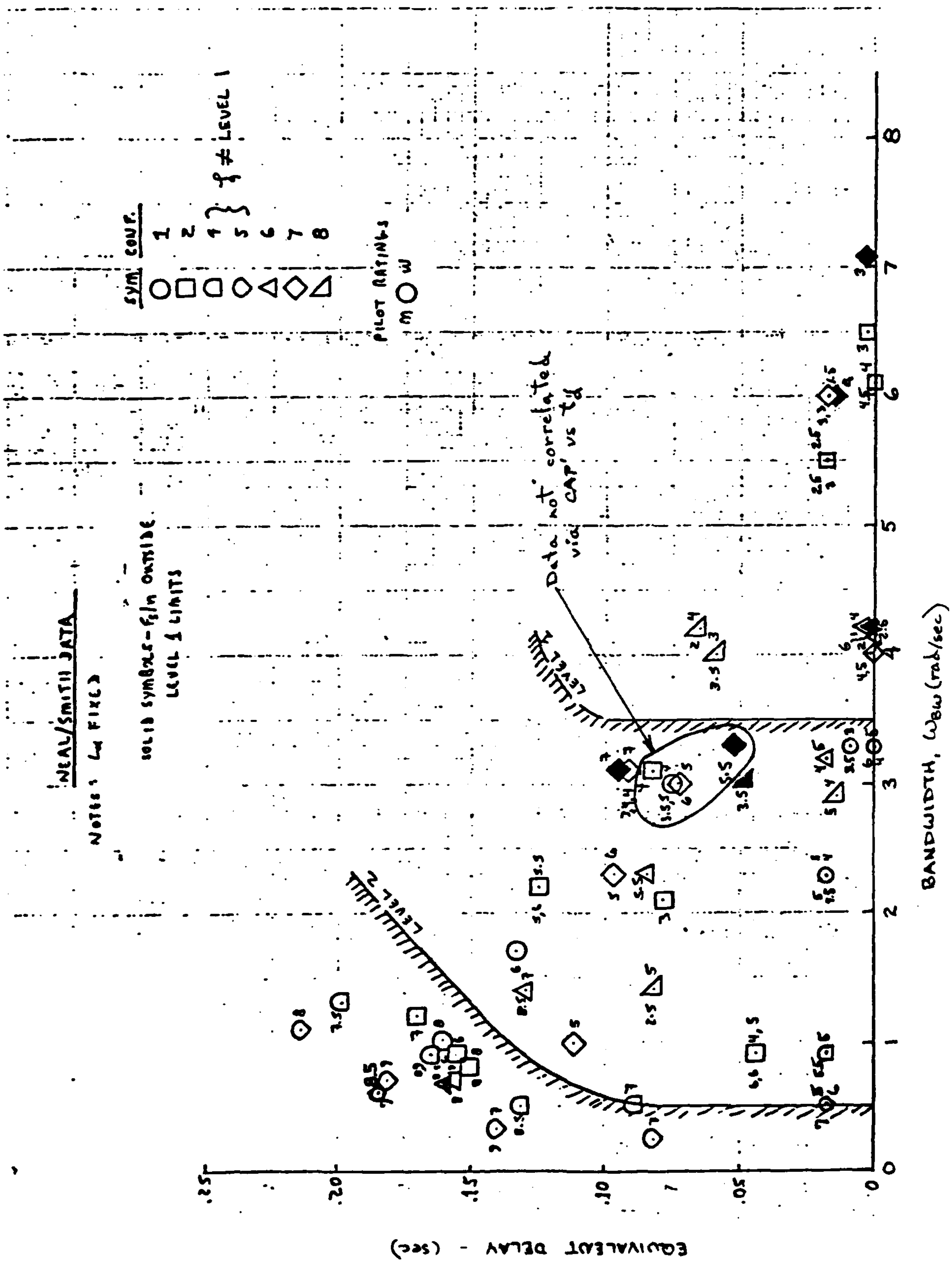


FIGURE 13. Bandwidth Criterion - NEAL-SMITH Data (Reference (j) figure)

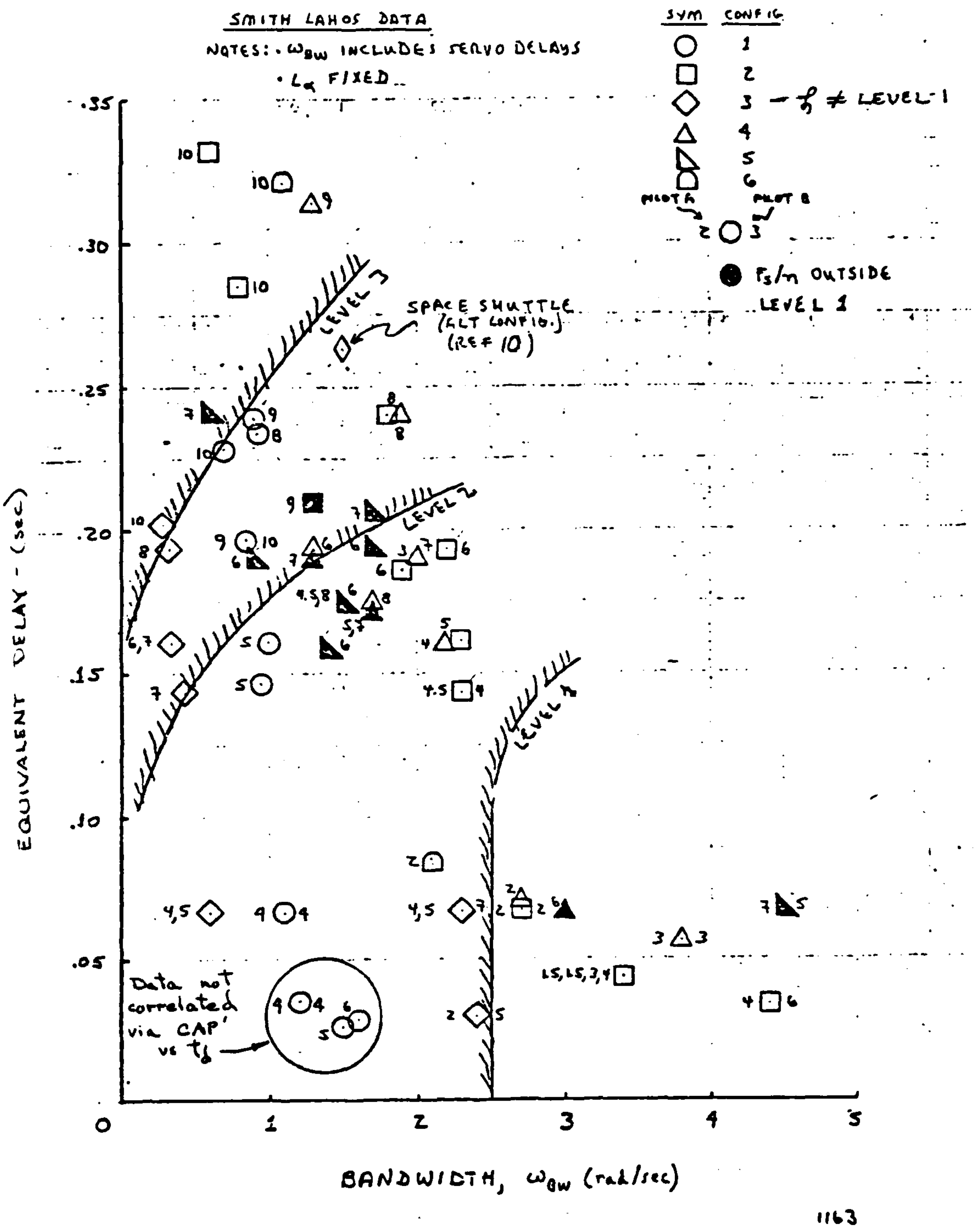


FIGURE 14. Bandwidth Criterion - LAHOS Data
(Reference (j) figure)

SUMMARY

A longitudinal control anticipation parameter has been defined which correlates high order augmented aircraft dynamics with both lower order equivalent descriptions and pilot opinion ratings. The approach has been verified with the data from two extensive in-flight flying qualities research programs which span the entire range of pilot opinion ratings. Additional effort is recommended to verify the minimum level 1 boundaries and to determine the relationship, if any, between the control anticipation and bandwidth parameters.

REFERENCES

a. Anonymous, MIL-F-8785B (ASG), "Military Specification, Flying Qualities of Piloted Airplanes," 7 Aug 1969

b. Bihrle, William, Jr., AFFDL-TR-65-198, "A Handling Qualities Theory for Precise Flight Path Control," Jun 1966

c. DiFranco, Dante A., AFFDL-TR-66-163, "Flight Investigation of Longitudinal Short Period Frequency Requirements and PIO Tendencies," Jun 1967

d. Anonymous, MIL-F-8785C, "Military Specification, Flying Qualities of Piloted Airplanes," 5 Nov 1980

e. Hodgkinson, J., LaManna, W. J. and Heyda, J. L. Aeronautical Journal Technical Note, "Handling Qualities of Aircraft with Stability and Control Augmentation Systems - A Fundamental Approach," Feb 1976

f. Neal, T. Peter and Smith, Rodgers E., AFFDL-TR-70-74, "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes," Dec 1970

g. Smith, Rogers E., AFFDL-TR-78-122 "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities," Mar 1978

h. Hodgkinson, J., and Buckley, J., "General Purpose Frequency Response Curve Fit," 25 Oct 1978

i. Johnston, K. A. and Hodgkinson, J., MDC Report No. MDC A5596, "Flying Qualities Analysis of an In-Flight Simulation of High Order Control System Effects on Fighter Aircraft Approach and Landing," 22 Dec 1978

j. Mitchell, David C. and Hoh, Roger H., Systems Technology Incorporated Working Paper No. 1163-1, "Review and Interpretation of Existing Longitudinal Flying Qualities Criteria for Use in the MIL Standard/Handbook," Dec 1980

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